

# Appendices to Vincent *et al.*: Biomimetics—its theory and practice

## 1 Appendix 1: Altshuller's 40 Inventive Principles with biological examples

### 1. Fragmentation

*Divide an object into independent parts; make it sectional or able to be dismantled; increase the degree of fragmentation or segmentation*

Division of an 'object' is seen in insect colonies, when groups of ants, bees or wasps act as a coherent unit when they defend the nest or swarm. Many animals are simply segmented (which probably makes them simpler to define at the genetic level) and most plants are modular (leaves, flowers, stem, root). Modern genetics shows that the underlying instructions are very similar, so that an insect's antenna can be persuaded to develop as a leg. Ease of dismantling is seen in autotomy and abscission mechanisms (abscission), in which parts of plants and animals can be made to fall off in a controlled manner. Examples are autumnal leaf fall and loss of limbs or tail by many animals when challenged. It is a general rule when designing a structure that compressive and tensile elements should be minimised and kept separate, and that either one (usually the compressive element) if reduced to zero will allow the least amount of the other element (tensile) to be used. This is seen in animals and plants with hydrostatic skeletons (which accounts for all non-woody plants). This can only be done with pre-stress (see Principle 9).

### 2. Taking out or extraction

*Extract the disturbing part or property from an object; extract only the necessary part (or property) of an object.*

Many animals or plants develop particular features at the expense of others. Flowers are a relatively late development in the evolution of plants, but are obviously successful in allowing the plant have a

specialised organ for reproduction. Similarly the pupal stage in many insects provides a separation between larva and winged adult, allowing a complete change in the morphology.

3. Local quality

*Change an object's structure, action, environment, or external influence/impact from uniform to non-uniform; make each part of an object function in conditions most suitable for its operation; make each part of an object fulfil a different and/or complementary useful function.*

Each internal organ in an animal has its own micro-environment, often surrounding itself with a membrane to emphasise this separation. Any organism has to be multifunctional, even a single cell, and so is very heterogeneous. There is much to be learned here regarding the optimisation between the various functions and the optimisations involved in spatial separation and functional integration. Invertebrates tend to allow more autonomy to their internal organs which possibly makes them more robust.

4. Asymmetry

*Change the shape or properties of an object from symmetrical to asymmetrical; change its shape to suit external asymmetries (e.g. ergonomic features); or if it is asymmetrical, increase its asymmetry.*

Very few biological objects are symmetrical and so are difficult to model and analyse. The asymmetry is usually a direct response to the usage or history of the object, and so represents an immediately adaptive and efficient response to function. Symmetry probably occurs in engineering only for ease of fabrication and calculation.

5. Merging/Consolidation

*Bring identical or similar objects, or operations in space, closer together (or merge them); make them contiguous or parallel.*

In segmented animals the nervous system is primitively divided into numbers of local units (ganglia) which tend to fuse in the more evolved members of the groups. This presumably allows faster central signal processing.

6. Universality

*Make an object perform multiple functions; eliminate the need for other parts; eliminate all idle or intermittent motion.*

The cuticle of arthropods is waterproof, the skeleton, a food store, a signalling system (sound and vision), and a sensing material. Wood

supports the tree and transports nutrient from the leaves and water to them.

7. Nested doll

*Place one object inside another; place multiple objects inside others; make one part pass (dynamically) through a cavity of the other.*

The female aphid reproduces parthenogenetically (i.e. without need of sperm). The nesting allows unborn aphids to have their offspring developing inside them, even several generations further on. The aphid can then reproduce extremely quickly when it finds itself on a good food supply, and ensures that all the individuals are genetically the same, which under these conditions ensures that they are all best adapted for that particular food source. This general principle can also be exemplified by deployable structures in insects, where many of them are made by the retraction of one segment or part inside another. Examples are stings, egg-laying tubes, tubular mouthparts.

8. Anti-weight

*To compensate for the weight of an object, merge it with other objects that provide lift or make it interact with the environment (use aerodynamic, hydrodynamic, buoyancy and other forces).*

Commonly used in locomotion (flight, swimming). Many animals are planktonic, floating in water but going up and down on a daily cycle. They do this either by active swimming or by changing their buoyancy. Many flying animals use upward currents of air (thermals, updrafts) in a similar fashion.

9. Preliminary anti-action, prestressing

*When it is necessary to perform an action with both harmful and useful effects, this should be replaced with anti-actions to control harmful effects; pre-stress in opposition to known undesirable working stresses.*

All non-woody plants are prestressed in tension which allows the amount of solid material in the structure to be minimised (see Principle 1). The provision of protection against the physical environment is a general property of living things - extreme examples are penguin feathers (against cold) and thick bark in eucalyptus trees which can peel off (protection against dust pollution and fire).

10. Preliminary action

*Perform the required change of an object in advance (totally or at least partly); arrange objects in such a way that they will come into action*

*from the most convenient place and without losing time for their delivery.*

This is a pre-requisite for survival. Organisms in temperate climates are linked to the seasons, so that (for instance) mating occurs at a suitable time for the offspring to be born when there is the most food around. In the shorter term hormones prepare us for various actions (an example is adrenalin). Jet lag is an expression of this phenomenon, in that we are physiologically prepared for sleeping in addition to responding to changes in external light conditions.

11. Beforehand cushioning

*Prepare emergency means to compensate for low reliability of an object ('belt and braces').*

The nervous system as a pattern analyser can extrapolate present observations to estimate the probability of future events. Organisms also have various degrees of redundancy and safety factors built in to their design to allow for failure rates in use. The failure rate is closely related to the reproductive rate of the organism - an organism which reproduces at a higher rate can afford greater loss of individuals.

12. Equipotentiality

*If an object has to be raised or lowered, redesign the object's environment to eliminate the need or have it performed by the environment.*

This comes into the general area of energy conservation, so any mechanism in which strain energy can store potential or kinetic energy for short times will be relevant. Examples are strain energy storage in locomotion, which is reduced by reducing inertia. That is why a running athlete folds his / her legs as far as possible on the recovery stroke, reducing the effective length of the leg.

13. The other way round

*Invert the action used to solve the problem (e.g. instead of refrigerating an object, heat it); make movable parts (or external environment) fixed, and fixed parts movable; invert the object (or process).*

Exodigestion of food by flies, spiders and some carnivorous plants, which spread or inject digestive enzymes over the food and resorb up the partially digested material; the eversible gut of a star fish which wraps itself around the prey item, thus eliminating 'swallowing'.

14. Spheroidality - Curvature

*Move from straight parts of an object to the curved ones, from flat sur-*

*faces to spherical ones and from parts shaped as a cube (parallelepiped) to ball-shaped structures; use rollers, balls, spirals; go from linear to rotary motion (or vice versa); use centrifugal force.*

Although there is only one rotating joint in nature, there are many examples of balls, spirals and domes, probably because they are relatively simple shapes to define (by internal pressure or by having an asymmetrical growing edge) and can produce structures which will take forces without generating shear through the thickness of the shell.

15. Dynamics

*Change the object (or outside environment) for optimal performance at every stage of operation, make them adaptable; divide an object into parts capable of movement relative to each other; change from immobile to mobile; increase the degree of free motion.*

The cells generally accept only low loads from the environment and bend out of the way of high loads, or readjust in the presence of (detected) high loads. The nervous system is necessary for detection; the muscular system is necessary for the readjustment in the short term, or growth in the long term.

16. Partial or excessive action. Abundance

*If you can't achieve 100 per cent of a desired effect then go for more or less.*

Control mechanisms in animals tend to be optimally damped, but at several levels. Peripherally (by basic inertial design and the actuation system) and centrally (by the nervous system).

17. Transition to another dimension

*Move into an additional dimension, from 1D to 2D, from 2D to 3D; go from single storey or layer to multi-layered; incline an object, lay it on its side; use the other side of the object; use light falling onto the neighbouring square or onto the other side of the given square.*

This is readily seen as an aspect of evolution and phylogeny. More primitive organisms tend to align themselves with environmental surfaces, probably because they lack the stiffness or stability to move away from them. Mosses grow on the ground or as low mounds; only in higher plants has a stem of sufficient stiffness been developed for the plant to raise itself off the substrate; more primitive anellids and molluscs tend to crawl along the ground, then become errant, moving in 3D.

18. Mechanical vibration

*Cause an object to oscillate or vibrate; increase its frequency; use its resonant frequency; use piezoelectric vibrators instead of mechanical ones; combine ultrasonic and electromagnetic field oscillations.*

There are many examples of oscillators in nature, presumably because once the conditions for a resonant frequency have been established it is not too difficult to maintain those conditions. Resonant frequencies are also very common in the mechanical parts of a locomotory system (leg-as-pendulum) and communication (producing noise).

19. Periodic action

*Instead of continuous action, use periodic or pulsating actions; if an action is already periodic, change the magnitude or frequency of the period; use periods between actions to perform a different action.*

Many insects communicate using modulation of a frequency rather than changing the basic frequency - presumably this is energy-efficient. The bombardier beetle produces a pulsed stream of hot phenols and peroxide which it can squirt at its predator at high velocity. Many organisms have down-time (sleep) built in to them either for reconstitution or because the daily cycle presents times when the environment is not optimal (too hot, too cold, too dark, too light).

20. Continuity of useful action

*Carry on work without a break; all parts of an object operate constantly at full capacity; eliminate idle and intermediate actions.*

In a constant environment (beyond the Polar circles) sleep tends to be absent or continuous depending on season. More highly evolved organisms tend to function at constant temperature.

21. Skipping/Rushing through

*Conduct a process or stages of it (e.g. destructive, harmful, hazardous operations) at high speed.*

The basilisk lizard can run across water if it pushes its feet down fast enough (this effect is limited by scaling). It implies high rates of energy dissipation which is not usual in biology. Obviously it could be applied to escape or avoidance behaviour, and so is really applicable only in emergency.

22. Blessing in disguise, turn harm into benefit

*Use harmful factors (from environment as well) to achieve a positive effect; eliminate the primary harmful action by adding it to another*

*harmful action to resolve the problem; amplify a harmful factor to such a degree that it is no longer harmful.*

Many organisms respond to minor damage by increasing their growth rate; plants being eaten by insects frequently grow more quickly. Many organisms have adapted to fire so it opens up the habitat and provides a sudden influx of nutrients as the burnt material dissolves into the soil, thus effectively reducing competition from other organisms. Many plants in hot and dry environments produce aromatics which accelerate and support fire.

23. Feedback

*Introduce feedback to improve the process of action; if feedback is already used, change its magnitude, sign (+ or -) or influence in accordance with operating conditions.*

Biology is replete with feedback mechanisms since they can greatly improve the performance of a wide variety of functions which are not mechanically perfect or optimised. A particularly good example is the use of feedback in frequency analysis in the middle ear.

24. Intermediary/Mediator

*Use an intermediary carrier article or intermediary process; merge one object temporarily with another.*

Parasitism.

25. Self-Service

*An object must service, modify, control or repair itself; use waste resources (energy, or substance).*

Flying locusts open the thoracic and 8th abdominal spiracles, allowing the air to run through the tracheae and cool the flight muscles. Many insects use the haemolymph to take heat away from the flight muscles in the thorax and radiate it from the abdomen.

26. Copying, operating with substitute

*Replace unavailable, complex, expensive, awkward or fragile object with simplified and inexpensive copies; replace an object, or process with optical copies or images. Employ in the course of this the change of the scale (increase or decrease copies); if visible optical copies are used, move to infrared or ultraviolet copies.*

'Copying' (reproduction) is one of the main features of a living organism. Mimicry in animals can be in the form of camouflage (copying aspects of the physical or plant environment) or warning colouration

(bright colours which imitate poisonous or dangerous animals - prevalent amongst insects). Some plants mimic the physical environment (e.g. *Lithops*). And of course the nervous system keeps a permanently updated virtual copy of the environment in store.

27. Cheap short-living objects.

*Replace an expensive object with a multiple of inexpensive objects, compromising certain qualities, such as service life.*

Many organisms reproduce at high rates producing less 'well designed' individuals which can grow more quickly, reproduce younger, and utilise a more ephemeral habitat.

28. Mechanical substitution

*Replace a mechanical system with a sensory one; replace mechanical with optical, acoustic, or olfactory; employ electrical, magnetic and electromagnetic fields for interaction with the object; move from the static to moving, from stable in time to changing, from non-structured to structured fields; employ fields in combination with the ferro-magnetic particles.*

Many organisms mark their territory - e.g. wolves urinating at strategic markers around the perimeter (smell) and the spring song of birds stakes their claim both to land and mates (sound).

29. Pneumatics and hydraulics

*Use gas and/or liquid parts of an object instead of solid parts (e.g. inflatable filled with liquid, air cushion, hydraulic, hydro-reactive).*

Since gas and liquid are metabolically cheap resources they are commonly used for skeletal functions (where water can take compressive pressure), flotation devices (teleost fish, Nautilus, *Sepia*, etc.) and locomotion ('jetting' squid).

30. Flexible shells and thin films

*Use flexible shells and thin films instead of 3D structures; isolate the object from its environment using flexible membranes.*

Non-woody plants are confined within a stiff epidermis which takes out most of the tensile forces within the structure; internal organs in animals are confined within a basement membrane; arthropods are essentially shaped from a single sheet of cuticle which is folded and expanded.

31. Porous materials

*Make an object porous or add porous elements (inlays, covers, etc);*

*if an object is already porous, use the pores to introduce a useful substance or function (impregnate the pores with some other substance).*  
 Wood is made of tubes with spirally wound fibres. These tubes transmit liquid when young and provide a tough light material when dead. Hedgehog spines and porcupine quills are cellular and very light and stiff

32. Colour change

*Change the colour or transparency of an object or its external environment; to improve visibility of things that are difficult to see, add colour or luminescent elements; change the emissive properties of an object subject to radiant heating.*

Squid and cuttlefish express complex behaviours (agonism, emotion?) by controlling colour cells in their skin. They, and many fish, can change colour to blend in with the background. They can also control their reflectivity. Many pelagic animals are translucent.

33. Homogeneity

*Objects interacting with the main object should be of same material (or material with identical properties).*

Many nests are made from the surrounding material - bird's nests (twigs, branches), solitary bee and termite nests (mud). The materials from which an organism is made are very inhomogeneous in texture, but basically only proteins and polysaccharides with added ceramic.

34. Rejecting, discarding-recovering, regenerating

*After completing their function (or becoming useless) reject objects, discard them (by dissolving, evaporating, etc.) or modify during the process; restore consumable/consumed parts of an object during operation.*

Cells contain an lysozyme for their dissolution and recycling; the tissues of amphibians, insects, etc are autolysed when they metamorphose; the exoskeleton of an insect can be partly dissolved for food; teeth of rodents and herbivorous insects grow continuously but are selectively worn away during feeding, so keeping a sharp edge.

35. Parameter change

*Change: the physical state (e.g. to gas, liquid, or solid), concentration, density, degree of flexibility, temperature, volume, pressure or any other parameter.*

Oxygen is transported attached to haemoglobin, which greatly in-

creases its 'solubility'; many animals and plants can survive being dried or frozen which enables them to live in marginal habitats; the stiffness of plants can be changed by internal pressure in cells, allowing movement. Echinoderms change the stiffness of their collagenous tissue. Most poikilothermic ('cold-blooded') animals and many plants can control their temperature within wide limits.

36. Phase transition

*Use phenomena of phase transition (e.g. volume change, loss or absorption of heat, etc.).*

The most important type of phase change is probably that from random polymeric to liquid crystal. This underlies the formation of many regular structures such as silk and many collagen structures; 'self-assembly'.

37. Thermal expansion

*Use thermal expansion or contraction of material; use multiple materials with different coefficients of thermal expansion.*

Temperature is rarely a variable, but water content is, and the mechanical consequences of change in turgor can be modelled by the same maths that is used for thermal change. Plants grow through concrete using only the expansion of their cells as water is attracted in to them up an osmotic gradient; dead plant parts can move because they expand by different amounts when they absorb water.

38. Strong oxidants

*Replace air with oxygen-enriched air or pure oxygen; expose air or oxygen to ionising radiation; use ionised oxygen; replace ozonised (or ionised) oxygen with ozone.*

A dangerous ploy for natural systems, but some specialists (e.g. the bombardier beetle) can cope with hot hydrogen peroxide! Otherwise this is a good description of many enzyme systems.

39. Inert medium or vacuum

*Replace a normal environment with an inert one; add neutral parts, or inert additives to an object; carry out the process in a vacuum.*

A similar move would be to add a protective coating, as happens when skin goes brown in the sun - the melanin absorbs the UV radiation. Many organisms can survive anaerobically, some obligate (e.g. *Trichonympha* which digest cellulose in termites).

40. Composite materials  
*Change from uniform to composite (multiple) materials.*  
 Very few biological materials are not composite  
 Additional principles suggested by Altshuller:
41. Employ time intervals. One operation is inserted in time intervals of another.
42. Employ gradual/cascade operation
43. Employ foam (similar to IP 31)
44. Employ inserts
45. Employ bi-principle
46. Employ explosives or gunpowders
47. Assembling (and other operations) on or in water
48. A sack with vacuum
49. Dissociation-association
50. Principle of self-organisation

It is obvious that most of these additional methods can be placed in the previous forty ones, but it is useful anyway, because it increases detail of the methods. If we add to any action/operation its anti-action as a principle; e.g. principle of rushing through (No.21) is a very strong method, but often it is very useful to make a process extremely slow. Or mechanical systems, which are currently substituted by electric, electronic, etc. systems appear to be more robust and reliable under some conditions (e.g. high levels of radiation, wide range of temperatures, etc.). Similarly all the principles can be made more 'biological' by adding the prefix 'Self-'

## **2 Appendix 2: Apportioning Altshuller's conflict features and inventive principles to the PRIZM categories**

### **2.1 Substance**

**Add, remove, change properties of a material**

- *Contradiction Matrix*

Weight of moving and stationary object (1, 2)  
Loss of substance (23)  
Quantity of substance (26)

- *Inventive Principles*  
Copying (26)  
Colour change (32)  
Homogeneity (33)  
Parameter change (35)  
Phase transition (36)

## 2.2 Structure

**Add, remove, regroup structural parts**

- *Contradiction Matrix*  
Stability of the object's composition (13)  
Manufacturing precision (29)  
Ease of manufacture (32)  
Device complexity (36)
- *Inventive Principles*  
Segmentation (1)  
Taking out (2)  
Local quality (3)  
Merging (5)  
Universality (6)  
Nested Doll (7)  
Abundance (16)  
Intermediary (24)  
Discarding and recovering (34)  
Composite materials (40)

## 2.3 Space

**Change position or shape of system or parts**

- *Contradiction Matrix*  
Length of moving and stationary object (3, 4)  
Area of moving and stationary object (5, 6)  
Volume of moving object (7)

Volume of stationary object (8)

Shape (12)

- *Inventive Principles*

Asymmetry (4)

Spheroidality, curvature (14)

Flexible shells and thin films (30)

Porous Materials (31)

Another dimension (17)

## 2.4 Time

### Change speed of process or order of actions

- *Contradiction Matrix*

Speed (9)

Duration of action of moving and stationary object (15, 16)

Loss of time (25)

Productivity (39)

- *Inventive Principles*

Preliminary Action (10)

Beforehand Cushioning (11)

Dynamics (15)

Periodic Action (19)

Continuity of useful action (20)

Rushing through (21)

Cheap short-lived objects (27)

## 2.5 Energy

### Change energy source or field

- *Contradiction Matrix*

Total force (10)

Stress or pressure (11)

Strength (14)

Temperature (17)

Illumination intensity (18)

Use of energy by moving and stationary object (19, 20)

Power (21)

Loss of energy (22)

- *Inventive Principles*
  - Anti-Weight (8)
  - Preliminary Anti-Action (9)
  - Equipotentiality (12)
  - Mechanical vibration (18)
  - Mechanics substitution (28)
  - Pneumatics and Hydraulics (29)
  - Thermal Expansion (37)
  - Strong oxidants (38)
  - Inert Atmosphere (39)

## 2.6 Information

### Change interactions or regulation of a system or its elements

- *Contradiction Matrix*
  - Loss of information (24)
  - Reliability (27)
  - Measurement accuracy (28)
  - Object-affected and object-generated harmful factors (30, 31)
  - Ease of operation and repair (33, 34)
  - Adaptability or versatility (35)
  - Difficulty of detecting and measuring (37, 38)
- *Inventive Principles*
  - The other way around (13)
  - Blessing in disguise (22)
  - Feedback (23)
  - Self-service (25)

## 3 Appendix 3: Examples of functions at various size scales in biology and technology

### 3.1 Biology

#### 3.1.1 Substance

- Molecule (nm): Enzyme
- Cell ( $\mu\text{m}$ ): Plants under water stress adapt by having a greater concentration of solutes in the cells and so can afford to lose water when

overheated. Phytohormones trigger cascades of signalling that result in cellular responses such as growth, differentiation, migration and survival.

- Organ (mm/cm): In a hydrostatic skeleton the internal liquid is under pressure, contained within a tensile body wall, that stiffens the organism. Fish and cetaceans reduce the energy cost of swimming with elastic tendons working in parallel with the muscles.
- Individual (cm/m): *Amoeba* moves on solid surface by converting jelly into liquid and liquid into jelly in its body
- Population (km): Cidarids have thick spines whose surface supports encrusting algae and small organisms, providing camouflage

### 3.1.2 Structure

- Molecule (nm): Diffracting structures with periodicities below the wavelength of light on the corneas of moths provide an antireflector.
- Cell ( $\mu\text{m}$ ): Graviceptive cells in plants: statoliths change their position in the direction of the gravity vector and thus mediate the gravitational response.
- Organ (mm/cm): Insect cuticle is multi-layer composite structure
- Organism (cm/m): Froghoppers (*Philaenus spumarius*) jump with thrust generated by the simultaneous extension of both hind legs in less than 1 ms. This force exerted is much higher per unit body mass than in other jumping animals
- Population (km): Social structures, hierarchies, etc.

### 3.1.3 Space

- Molecule (nm): The globular architecture of growth factors is essential for cell receptor binding.
- Cell ( $\mu\text{m}$ ): Membrane pores regulate osmosis.
- Organ (mm/cm): The root hairs of plants increase the absorptive surface. When two spatially separated eyes look at an object, each retina receives a slightly different view of the object. The disparity varies as the distance between the eye and the object.

- Organism (cm/m): The dung beetle makes balls of dung and rolls them in order to move them easily over a long distance.
- Population (km): Animals divide space into territories which reduces conflict and competition for resource.

#### 3.1.4 Time

- Molecule (nm): Synapse delay; saw-tooth oscillations.
- Cell ( $\mu\text{m}$ ): Metabolic rate regulates temperature.
- Organ (mm/cm): Morpho-functional features of the cardiac performance of the icefish: the heart ventricle is a low rate, low pressure, high volume pump which is adaptive for low temperature.
- Organism (cm/m): The hunting activity of the beetle *Philonthus* is made up of a chain of responses, released by at first visual, then olfactory, then tactile stimuli in succession.
- Population (km): Social and ecological successions.

#### 3.1.5 Energy

- Molecule (nm): Manipulation of phosphate bonds.
- Cell ( $\mu\text{m}$ ): Fixed stable position and optimal cell orientation in the gravitational field as a state of mechanical stress of the cytoskeletal elements and those that maintain the cell membrane.
- Organ (mm/cm): Woodpecker uses kinetic energy to increase force.
- Organism (cm/m): The tumbleweed uses energy from the wind for locomotion. The ears of the moth *Ormia* are connected by a mechanical structure that uses two resonant modes of vibration which provides directional high-frequency hearing. The electric fish uses the electric charge and electric field for self-defence and orientation in murky water, operating at a distance.
- Population (km): Trophic chains - autotrophs, heterotrophs, herbivores, carnivores; omnivores

### 3.1.6 Information

- Molecule (nm): DNA, RNA store and transfer information about the amino acid sequences.
- Cell ( $\mu\text{m}$ ): Network architecture takes advantage of noise to initiate and maintain the respiratory rhythm. The population of pacemaker cells cooperates to maintain the rhythm only if the the background level of noise becomes too low.
- Organ (mm/cm): Muscles produce CO<sub>2</sub> which stimulates blood vessels to enlarge.
- Organism (cm/m): Censoring tropisms, Conditioning, Thinking, Decision-making
- Population (km): Learning, Information exchange, knowledge management

## 3.2 Technology

### 3.2.1 Substance

- Nanotechnology (nm): Adding oxygen to silicon creates silicon nanostructures.
- Materials ( $\mu\text{m}$ ): Embedding hydrogen in metals increases its thermal expansion.
- Products (simple tools) (mm/cm): Paints are used for colouring and protection from corrosion.
- Large products (cm/m): Material properties that minimise weight.
- Distributed systems (km): Different substances can be used for carrying information - newspapers, hard drives, CD, etc.

### 3.2.2 Structure

- Nanotechnology (nm): Non-linear optic fibre transfers light impulse into the soliton.
- Materials ( $\mu\text{m}$ ): Deformation increases the speed of steel corrosion.
- Products (simple tools) (mm/cm): Swiss army knife.

- Large products (cm/m): Catamaran - new properties with changing the number of parts.
- Distributed systems (km): Bridges, road marks in traffic control.

### 3.2.3 Space

- Nanotechnology (nm): Contaminating particles adhere to the surface of the droplet and are removed when the droplet rolls off.
- Materials ( $\mu\text{m}$ ): Spinning optic fibres increases the speed of light transfer.
- Products (simple tools) (mm/cm): The shape of a tool handle is designed to give maximum control with minimum effort.
- Large products (cm/m): To conserve energy a house should be round (ideally globular).
- Distributed systems (km): Spaghetti junctions.

### 3.2.4 Time

- Nanotechnology (nm): Increasing the speed of an elementary particle prolongs its life.
- Materials ( $\mu\text{m}$ ): The speed of the sound source changes the frequency of the sound received.
- Products (simple tools) (mm/cm): An electric toothbrush speeds up brushing.
- Large products (cm/m): Rotary excavator (non-stop process).
- Distributed systems (km): Time table for transport systems.

### 3.2.5 Energy

- Nanotechnology (nm): Light and electric field create charge in semiconductor nanostructure.
- Materials ( $\mu\text{m}$ ): Pressure changes the speed of sound in a gas.
- Products (simple tools) (mm/cm): Hot air balloon.

- Large products (cm/m): Steam, diesel, petrol, jet engines.
- Distributed systems (km): Electrical distribution grid.

### **3.2.6 Information**

- Nanotechnology (nm): Paramagnetic crystals show magnetic properties only when subjected to an external magnetic field (regulated properties).
- Materials ( $\mu\text{m}$ ): Shape memory alloy.
- Products (simple tools) (mm/cm): Thermostat. Global positioning system.
- Large products (cm/m): Aircraft cockpit.
- Distributed systems (km): Traffic control system.